Defocus-specific contrast sensitivity

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Chapter Six

Effect of methods of myopia correction on visual acuity, contrast sensitivity, and depth of focus

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Abstract

Purpose: To psychophysically measure spherical and irregular aberrations in patients with various types of myopia correction.

Setting: Laboratory of Experimental Ophthalmology, University of Groningen, Groningen, The Netherlands.

Methods: Three groups of patients with low myopia correction (spectacles, soft contact lens, and Intacs™) and 4 groups with high myopia correction (spectacles, rigid contact lens, Artisan™ claw lens, and laser in situ keratomileusis [LASIK]) had through-focus contrast sensitivity measurements to establish the myopic shift and depth of focus. From these 2 parameters, spherical and irregular aberrations were determined using theoretical eye models and geometric optics. Visual acuity, stray light, and predictability were also studied.

Results: There were no differences in best corrected visual acuity (BCVA) or best corrected contrast sensitivity between the low myopia groups. The Intacs™ group had a significantly larger depth of focus ($P < .05$). The results in the soft contact lens group were comparable to those in a human eye model with an average amount of spherical and irregular aberrations. The LASIK group had worse uncorrected visual acuity (UCVA) and best corrected contrast sensitivity than the spectacles, rigid contact lens, and Artisan™ claw lens groups ($P < 0.05$) due to the amount of spherical and irregular aberrations present after LASIK. The low and high myopia spectacles groups had average amounts of spherical and irregular aberrations.

Conclusions: Neither surgical techniques nor contact lenses resulted in BCVA or best corrected contrast sensitivity that surpassed the values measured in the best corrected spectacles groups. The Artisan™ claw lens performed better than LASIK in UCVA, predictability, and best corrected contrast sensitivity.

Introduction

Today, myopic individuals have various options for correction of their refractive anomaly. Least invasive are spectacles, an option that is not always cosmetically acceptable or practical. More invasive are contact lenses, an option that also has disadvantages in that wearing lenses can be impractical and contact-lens-related complications or intolerance can occur. Most invasive are refractive surgery techniques. There are several types of techniques to choose from when spectacles and contact lenses are not options. Each uses a different approach to correct myopia. One approach is to reshape the cornea by implantation of intracorneal ring segments (Intacs™, Keravision Inc.) or excimer laser techniques (photorefractive keratectomy [PRK], laser in situ keratomileusis [LASIK], and laser-assisted subepithelial keratectomy). The disadvantage of the Intacs™ technique is its relatively narrow dioptric indication; myopia up to -4.0 diopters (D).[1] The advantage is that it is reversible; ie, explantation is possible if the patient is dissatisfied.[2] The excimer laser techniques have the disadvantage of irreversibly reshaping the cornea. Another reversible approach is to implant an intraocular lens (IOL). One example is the Artisan™ claw lens (Ophtec BV).[3]

Each technique can induce different types and amounts of aberrations. Spherical and irregular aberrations are known to influence the quality of vision. Although vision quality is a subjective term, it comprises measurable variables such as visual acuity, contrast sensitivity, stray light, and depth of focus. These psychophysical variables can function as indicators of the amount of spherical and irregular aberration.[4] Measuring aberrations psychophysically can supplement objective measurements with double-pass laser techniques, wavefront sensors, and aberrometers. Although some optical parameters correlate with psychophysical ones, eg, visual acuity and area under the contrast sensitivity function,[5] psychophysical measurements evaluate functional spatial vision after refractive surgery more directly. To our knowledge, no study using a single experimental protocol has measured these variables in patients with spectacles, Intacs™, soft and rigid contact lenses, and Artisan™ claw lenses and in those who had LASIK.

The present study determined visual acuity, stray light, and through-focus contrast sensitivity with various methods of refractive surgery and compared the results with those of conservative methods of myopia correction. Derivatives of through-focus contrast sensitivity such as depth of focus and myopic shift were also calculated to evaluate the spherical and irregular aberrations present in each correction group.

Patients and Methods

Types of Myopia Correction

Patients with high myopia, arbitrarily defined as a refractive error requiring a spherical-equivalent spectacle correction of at least –8.0 D, were distinguished from those with low myopia, ie, a spherical equivalent correction between –1.0 and –6.0 D. The more conventional corrective methods of spectacles and contact lenses (soft contact lenses in individuals with low myopia and rigid contact lenses in those with high myopia) were compared to surgical methods: Intacs™ for low myopia and LASIK and the Artisan™ claw lens for high myopia.

Patients and Surgical Techniques

The spectacles and contact lens groups consisted of subjects recruited via advertisements in local newspapers. Consequently, the contact lens material and size represented a random selection of the lenses used by the people of Groningen. Intacs™ implantation was performed by 3 surgeons (1 of whom had operated on 7 of the 10 patients) at the University Hospital Groningen between May 1997 and December 1998. Briefly, under topical anesthesia, 2 intracorneal ring segments were placed nasally and temporally through a 1.8 mm incision at the 12 o'clock position at least 1.0 mm from the incision site in peripheral stromal channels that were created with specially designed blunt dissectors.

Laser in situ keratomileusis was performed by a single surgeon at the Rotterdam Eye Hospital between October 1996 and February 1998; a broad-beam excimer laser (Technolas® Keracor 116, Bausch & Lomb) was used. For corrections less than –12.0 D, a nasally hinged corneal flap with a diameter of 8.0 to 9.0 mm and a base plate of 160 microns was created with the Automated Corneal Shaper (Bausch & Lomb). For larger corrections, the base plate was 130 microns. The mean optical zone diameter was 6.3 mm ± 0.4 (SD). The Artisan™ claw lens was implanted by a single surgeon in Stadskanaal, The Netherlands, between April 1990 and January 1998. The surgical technique has been described.[3]

All participants in the study signed an informed consent form. There were 10 patients in each group studied except the soft and rigid contact lens groups, which contained 8 and 7, respectively. The study was approved by the Ethics Committee of the University Hospital Groningen.

To ensure inclusion of a population without ocular pathology, all participants had the same routine ophthalmologic screening described by Nio *et al.*[6]: measurement of visual acuity, optical correction, corneal curvature, intraocular pressure, slitlamp examination, ophthalmoscopy, intraocular stray light (determined with the direct compensation method described by van den Berg and Spekreijse[7]), and biometry.

Psychophysical Measurement of Contrast Sensitivity

The experimental setup and psychophysical testing method used in this study were similar to those used by Nio *et al.*[6] Briefly, contrast sensitivity was measured using the von Békésy tracking method and vertical sinusoidally modulated gratings, displayed on a monitor screen (Joyce DM4, P31 phosphor, peak wavelength 520 nm, luminance 600 td) that extended 6 degrees x 6 degrees. Two drops of cyclopentolate hydrochloride 1% with a 30-minute interval between drops were administered before contrast-sensitivity measurements to prevent accommodation and ensure stable pupil dilation. Defocus level zero was defined as the optimal optical correction in mydriasis measured with an Early Treatment Diabetic Retinopathy Study letter chart at a viewing distance of 2 m. Contrast sensitivity at 6 spatial frequencies (1 cycles per degree [cpd], 2 cpd, 4 cpd, 8 cpd, 16 cpd, and 32 cpd) was measured at the same viewing distance. The contrast sensitivity function was determined in each group at 3 pupil diameters (4.0 mm, 6.0 mm, and 7.0 mm) and 6 levels of defocus (-2.0 D, -1.0 D, -0.5 D, defocus level zero, +1.0 D, and uncorrected except for a +0.5 D lens to correct for the viewing distance of 2 m). In the case of subjects with spectacles, 'uncorrected' in the visual acuity and contrast sensitivity measurements meant the subjects wore their spectacle correction in addition to the +0.5 D correction for the viewing distance. Similarly, contact lens subjects wore their contact lenses in the 'uncorrected' condition. Optical correction, defocusing lenses, and artificial pupils were put in a trial frame that subjects wore during the contrast sensitivity measurements. Spatial frequencies in the high myopia spectacles group were corrected for the size-reducing effect of the negative lenses (note 22 in Legge and coauthors[8]).

Data Processing: Statistical Analysis, Myopic Shift, and Depth of Focus

Data in this study were processed in the manner described by Nio *et al.*[4] Briefly, contrast sensitivity is the inverse of contrast at threshold. According to Michelson, contrast is:

$$\text{Contrast} = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} \tag{1}$$

where L_{max} represents the maximum and L_{min} the minimum luminance of a sine wave pattern. An analysis of variance (ANOVA) (SPSS 10.0, general linear model [GLM] for repeated measurements) was performed to investigate the effects of between-subject factors (method of myopia correction) and within-subject factors (pupil diameter, defocus, and spatial frequency). Where necessary, the Bonferroni correction for multiple comparisons was applied. All data for the 32 cpd spatial frequency were deleted from analysis because some subjects could not detect these gratings even at defocus level zero.

Optimum focus for contrast sensitivity depends on the spatial frequency measured; ie, the optimum focus for low spatial frequencies was more myopic than that for high spatial frequencies. This effect could only be attributed to spherical aberration.[9,10] As a measure of spherical aberration, myopic shift was defined as the difference between optimum focus for contrast sensitivity at 4 cpd and 16 cpd. Optimum focus at these spatial frequencies was determined by fitting a parabola to the averaged and the individual contrast sensitivity values as a function of defocus. The parabola was fitted to the highest contrast sensitivity value measured and the 2 adjacent points. The focus at which the top of the parabola was located was considered the optimum focus of the spatial frequency concerned. As a rule, the optimum focus at 4 cpd was located at a more negative focus than that at 16 cpd. The experimental myopic shift was then compared with the shift in 4 theoretical eye models: the reduced eye and Gullstrand's number 1 schematic eye, both described by Emsley,[11] and eye models 1 and 2 described by Jansonius and Kooijman.[10] The latter 2 models estimate a typical upper limit and an average amount of spherical aberration of the human eye, respectively. The myopic shift in these 2 models was described for different values of irregular aberration by Nio *et al.*[4] The irregular aberration consisted of a random distribution of dioptric power around a mean value. Van den Brink[12] found that this random distribution could be described by a normal distribution with a standard deviation of 0.5 D. Nio *et al.*[4] modelled different amounts of irregular aberration by varying this standard deviation.

Analysis of topographic pictures made by a corneal topographer (TMS-1 version 1.61, Computed Anatomy) resulted in the average spherical aberration of the cornea, assuming a 6.0 mm pupil. The method of analysis is described by Nio *et al.*[4]

One definition of the depth of focus for a specific spatial frequency is the dioptric range at which contrast sensitivity for that spatial frequency exceeds half its maximum value.[8] The depth of focus was evaluated at a spatial frequency of 8 cpd, an intermediate between the frequencies important for reading newspaper letters (12 cpd) and detecting edges (3 cpd).[13,14] To determine depth of focus, a curve was fitted through the averaged and individual contrast sensitivity data points as a function of defocus using a standard spline routine (EasyPlot V4, Spiral Software). Infrequently, the contrast sensitivity in a subject did not fall below half the maximum value at the –2.0 D defocus level. Because of this, the depth of focus was defined as twice the positive half of the dioptric range in which contrast sensitivity exceeds half the maximum value.

Results

Stray Light, Visual Acuity, and Predictability

Tables 1 and 2 describe the low and high myopia groups in terms of age, stray light, axial length, spherical equivalent refraction before and after myopia correction, predictability, and visual acuity after myopia correction (best corrected [BCVA] and uncorrected [UCVA]). There were no significant differences in age, axial length, or spherical equivalent refraction before myopia correction or BCVA after myopia correction between the 3 low myopia groups and the 4 high myopia groups ($P > .05$). Soft and rigid contact lenses caused more stray light than other methods of myopia correction in the low and high myopia groups ($P < .05$).

With low myopia, predictability was best in the spectacles and Intacs™ groups. It was comparable in these 2 groups and slightly better than in the soft contact lens group. After myopia correction, the UCVA was better in the spectacles group than in the soft contact lens and Intacs™ groups ($P < .05$). The latter 2 did not differ significantly from each other.

Table 1. Characteristics of the low myopia groups.

Characteristic	Spectacles	Soft Contact Lens	Intacs
Number of subjects	10	8	10
Age (y)	27 ± 6	30 ± 7	35 ± 9
Stray light [$\log(\varphi^2 \cdot L \cdot E^{-1})$][7]	0.85 ± 0.10	1.02 ± 0.12	0.80 ± 0.09
Axial length (mm)	24.2 ± 1.0	24.0 ± 0.9	24.8 ± 1.0
Spherical equivalent (D)			
Before myopia correction	-3.4 ± 1.6	-3.4 ± 1.1	-2.9 ± 0.9*
After myopia correction	0.2 ± 0.3	0.2 ± 0.5	-0.1 ± 0.6
Predictability (%)			
± 0.5 D	70	63	70
± 1.0 D	100	88	90
Best corrected visual acuity+	1.22 ± 0.23	1.30 ± 0.11	1.25 ± 0.21
Uncorrected visual acuity after myopia correction#	1.21 ± 0.18	0.81 ± 0.30	0.80 ± 0.28

Mean ± SD

* Spherical equivalent correction was measured preoperatively in the case of Intacs™.

\+ Visual acuity was measured with correction of remaining refractive errors after initial myopia correction.

\# "Uncorrected" means measurements were made while unoperated subjects wore their spectacles or contact lenses.

Table 2. Characteristics of the high myopia groups.

Characteristic	Spectacles	Rigid Contact Lens	Artisan Claw Lens	LASIK
Number of subjects	10	7	10	10
Age (y)	28 ± 9	38 ± 11	33 ± 8	33 ± 11
Stray light [log ($\varphi^2 \cdot L \cdot E^{-1}$)][7]	0.83 ± 0.08	1.09 ± 0.11	0.96 ± 0.18	0.94 ± 0.17
Axial length (mm)	26.8 ± 1.1	27.8 ± 1.1	26.6 ± 1.3	26.4 ± 0.9
Spherical equivalent (D)				
Before myopia correction	-9.9 ± 1.1	-13.0 ± 4.0	-10.2 ± 1.7 *	-10.6 ± 2.0 *
After myopia correction	-0.5 ± 0.8	0.1 ± 0.6	0.1 ± 0.5	-0.1 ± 1.2
Predictability (%)				
± 0.5 D	60	43	60	10
± 1.0 D	80	86	90	70
Best corrected visual acuity+	1.11 ± 0.17	1.01 ± 0.19	1.14 ± 0.17	0.91 ± 0.20
Uncorrected visual acuity after myopia correction#	1.08 ± 0.17	0.78 ± 0.24	0.77 ± 0.21	0.54 ± 0.13

Mean ± SD
BCVA = best corrected visual acuity; LASIK = laser in situ keratomileusis;
UCVA = uncorrected visual acuity
* Spherical equivalent correction was measured preoperatively in the groups that had surgery.
\+ Visual acuity was measured with correction of remaining refractive errors after initial myopia correction.
\# "Uncorrected" means measurements were made while unoperated subjects wore their spectacles or contact lenses.

With high myopia, predictability was best in the Artisan™ claw lens group, followed by the spectacles, rigid contact lens, and LASIK groups. This did not, however, result in a significantly higher UCVA in the Artisan™ claw lens group than in the rigid contact lens group ($P = 1.0$) and LASIK group ($P = .053$). The spectacles group had a significantly higher UCVA, ie, acuity measured while wearing spectacles, than the other 3 groups ($P < .05$).

Contrast Sensitivity

At defocus level zero, ie, with best correction, there was no significant difference in contrast sensitivity at any condition measured between the low myopia groups. *Figure 1A* shows the contrast sensitivity functions at defocus level zero with a 6.0 mm pupil in the soft contact lens and Intacs™ groups in relation to the 95% confidence interval (CI) in the spectacles group. In the high myopia groups (*Figure 1B*), the contrast sensitivity function at defocus level zero with LASIK was lower than that in the other groups in almost all the conditions measured. The LASIK group differed from the spectacles group at larger pupil diameters around the contrast sensitivity peak ($P < .05$).

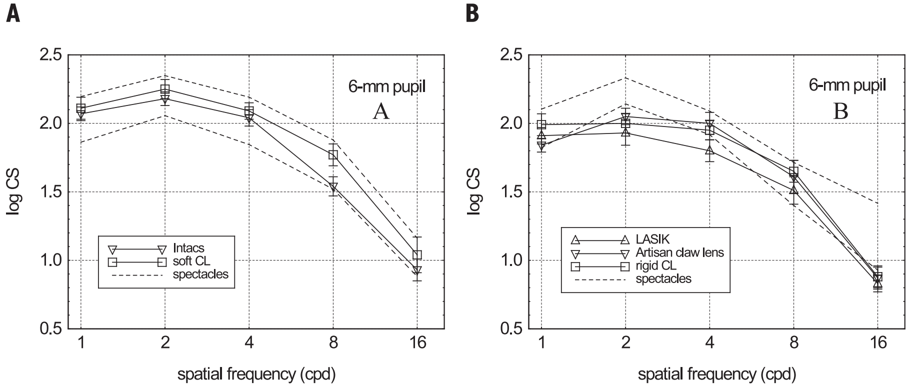

Figure 1.
Best corrected contrast sensitivity function, ie, at defocus level zero, of low (A) and high (B) myopia groups for a pupil diameter of 6.0 mm. The dotted lines represent the 95% CI based on the spectacles group.

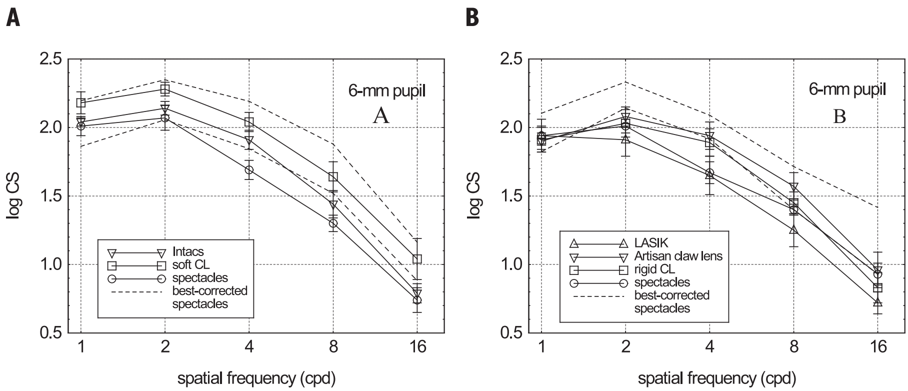

Figure 2.
Uncorrected contrast sensitivity functions of low (A) and high (B) myopia groups with a pupil diameter of 6.0 mm. In the spectacles group, "uncorrected" means measurements were made while subjects wore their own refractive correction. Dotted lines represent the 95% CI based on the best corrected spectacles group, ie, at defocus level zero.

Figures 2A and *B* show the uncorrected contrast sensitivity functions with a 6.0 mm pupil in the low and high myopic groups, respectively. In the low myopia groups, contrast sensitivity in the spectacles group was lower than that in the soft contact lens group ($P < .05$). The Intacs™ group did not differ from the spectacles or the soft contact lens group. Statistical analysis did not demonstrate a significant difference in uncorrected contrast sensitivity between the high myopia groups.

Analysis of contrast sensitivity data

To investigate the effect of all within-patient (pupil diameter, level of defocus, and spatial frequency) and between-patient (method of myopia correction) factors, an ANOVA was performed with a GLM for repeated measurements. Averaged over all methods of myopia correction, the results show an expected effect of pupil diameter, defocus level, and spatial frequency (not shown). The effect of pupil diameter on contrast sensitivity was not dependent on the level of defocus (not shown).

The differences between groups in within-patient variables were notable. In the low myopia group, a significant interaction was found between the method of myopia correction and the level of defocus (*Figure 3*): The optimum focus of contrast sensitivity in the spectacles group was located more to the myopic side than in the other groups, suggesting a higher spherical aberration in the spectacles group.

In the high myopia groups, significant interactions between the method of myopia correction and the defocus level (*Figure 4*), the method of myopia correction and the spatial frequency (*Figure 5*), and the method of myopia correction, defocus level, and spatial frequency (*Figure 6*) were found. *Figure 4* shows a more myopically located optimum focus of contrast sensitivity in the spectacles group. *Figure 5* shows that the spectacles group had a higher contrast sensitivity function averaged over all pupil diameters and levels of defocus than the other groups. *Figures 6A-D* illustrate that the optimum focus of contrast sensitivity for a spatial frequency of 4 cpd is located more to the myopic side in the spectacles and LASIK groups than in the other groups. The overall contrast sensitivity in the spectacles group was significantly higher than in the LASIK group ($P < .05$). No other comparisons of overall contrast sensitivity between the high myopia groups showed a significant difference.

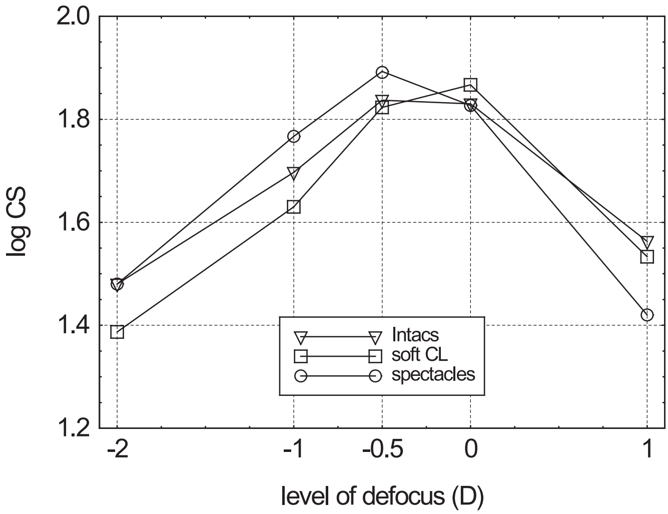

Figure 3
Contrast sensitivity, averaged over all measured spatial frequencies and pupil diameters, as a function of the level of defocus in the low myopia groups.

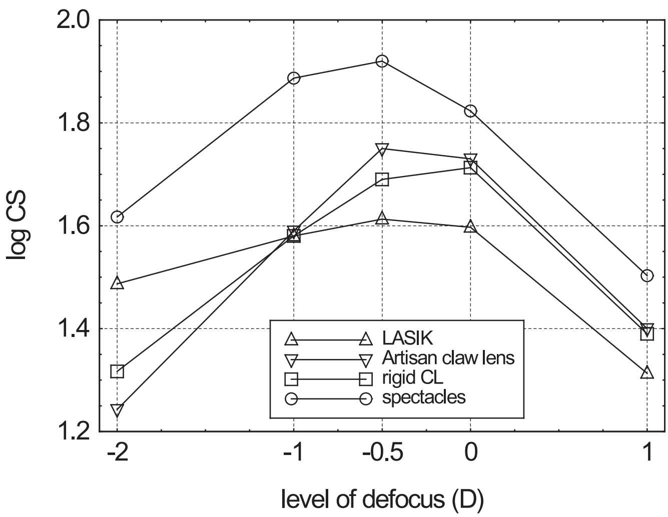

Figure 4
Contrast sensitivity, averaged over all measured spatial frequencies and pupil diameters, as a function of the level of defocus in the high myopia groups.

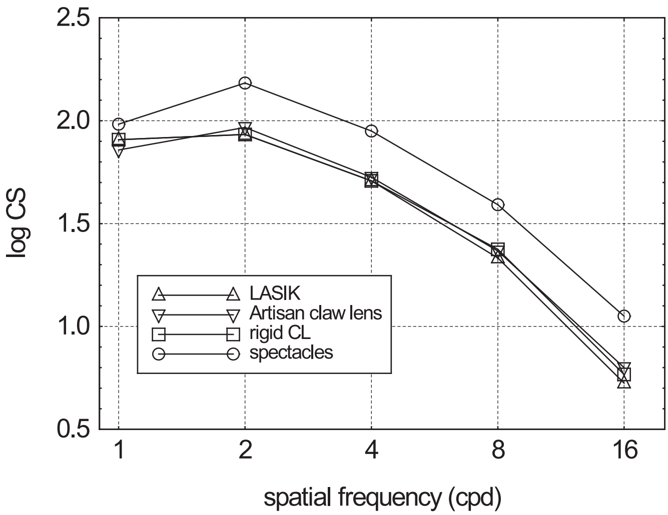

Figure 5.
Contrast sensitivity, averaged over all measured levels of defocus and pupil diameters, as a function of spatial frequency in the high myopia groups.

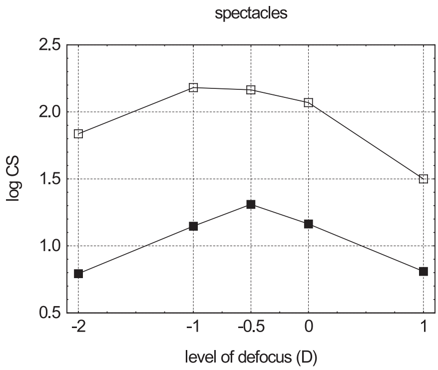

Figure 6A.

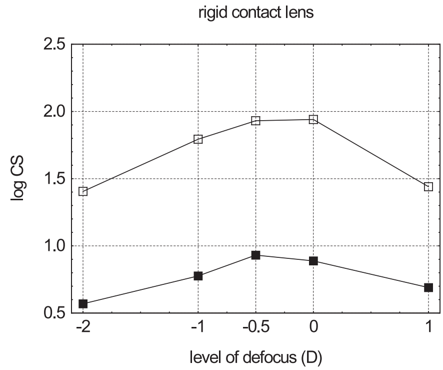

Figure 6B.

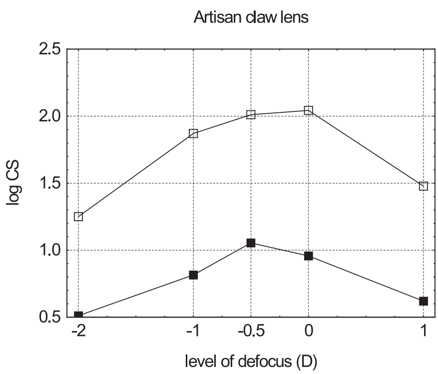

Figure 6C.

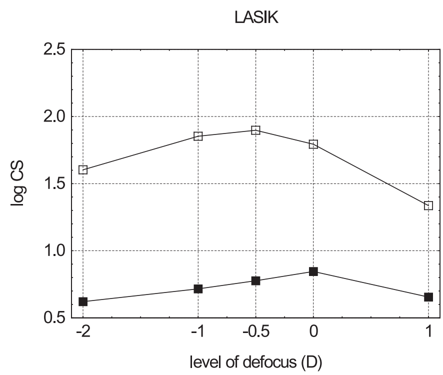

Figure 6D.

Figure 6. Contrast sensitivity, averaged over all pupil diameters, as a function of the level of defocus at 2 spatial frequencies (4 cpd and 16 cpd) measured in the high myopia groups. (A) Spectacles group. (B) Rigid contact lens group. (C) ArtisanTM claw lens group. (D) LASIK group.

Estimation of the Spherical Aberration

Tables 3 to *5* present the experimental and theoretical myopic shift data, the measure of spherical aberration used in the study. The experimental data are shown on the basis of the averaged and individual contrast sensitivity data. The effect of spherical aberration was analyzed with a 6.0 mm pupil because a smaller pupil limits spherical aberration. The myopic shift in the spectacles group was larger than that in the Intacs™ group ($P < .01$) in low myopia patients, and the shift in the LASIK group was larger than that in the Artisan™ claw lens group ($P = .02$) in high myopia patients.

Table 3. Experimental myopic shift in low myopia groups with a 6.0 mm pupil determined on the basis of the averaged and individual contrast sensitivity curves as a function of defocus.

	Experimental Myopic Shift (D)	
Group	Averaged	Individual (Mean ± SE)
Spectacles	-0.13	-0.41 ± 0.16
Soft contact lens	-0.22	-0.01 ± 0.12
Intacs	0.39	0.36 ± 0.12

Table 4. Experimental myopic shift in the high myopia groups with a 6.0 mm pupil determined on the basis of the averaged and individual contrast sensitivity curves as a function of defocus.

	Experimental Myopic Shift (D)	
Group	Averaged	Individual (Mean ± SE)
Spectacles	-0.57	-0.39 ± 0.14
Rigid contact lens	-0.03	0.19 ± 0.15
Artisan claw lens	0.34	0.23 ± 0.14
LASIK	-0.91	-0.57 ± 0.26

Table 5. Myopic shift for the theoretical reduced eye, schematic eye, and eye models 1 and 2 with a 6.0 mm pupil. Various amounts of irregular aberration (IA) were implemented in the theoretical eye models.

	Theoretical Myopic Shift (D) at		
Model	IA = 0.3 D	IA = 0.5 D	IA = 0.7 D
Reduced	-1.03	-1.00	-0.90
Schematic	-0.64	-0.60	-0.67
Eye model 1	-0.67*	-0.53*	-0.29*
Eye model 2	-0.28*	-0.33*	-0.22*

* From Nio et al.[4]

Figure 7 shows the spherical aberration in the cornea in each group calculated on the basis of corneal topography pictures. Some methods of myopia correction, eg, Intacs™, LASIK, and rigid contact lenses, involve alterations at the periphery of the cornea. The spherical aberration of the entire cornea calculated on the basis of the central 2.0 mm, presuming acompletely spherical cornea, was therefore compared with that calculated on the basis of the central 6.0 mm, in which a correction was performed for the actual (aspheric) peripheral corneal shape. In the low myopia groups, there was no difference between the spectacles and soft contact lens groups in the total corneal spherical aberration. The difference between the Intacs™ group and the other 2 groups ($P < .01$) was caused by the corneal periphery of the Intacs™, which had a more pronounced aspheric shape that attenuated the corneal spherical aberration. In the high myopia groups, the total corneal spherical aberration in the LASIK group differed from that in the other groups

($P < .01$); no difference was found between the spectacles, rigid contact lens, and Artisan™ lens groups. The central part of the LASIK cornea was comparable to that in the other groups, but the periphery had a more spherical shape, resulting in a much higher spherical aberration.

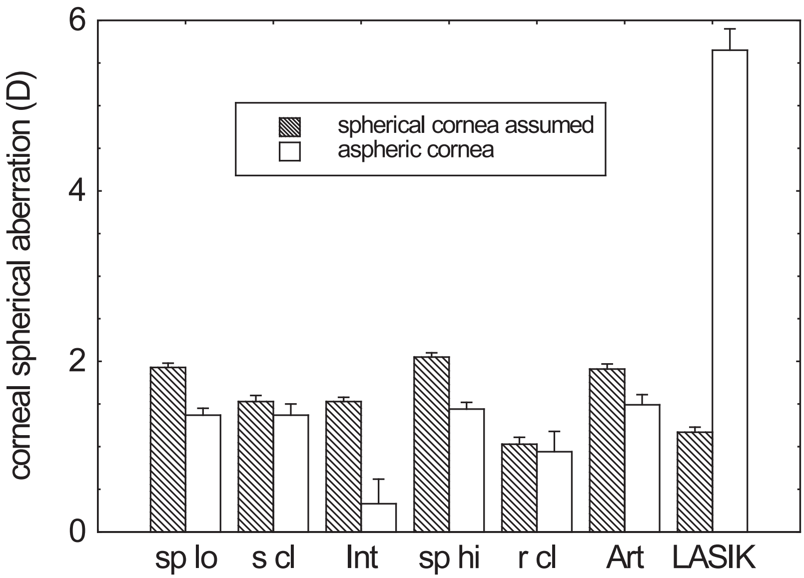

Figure 7.
Corneal spherical aberration on the basis of the central 2.0 mm (assuming a spherical shape of the cornea) and the central 6.0 mm (corrected for the aspheric flattening of the corneal periphery) of the cornea in all measured groups: low myopia spectacles (sp lo), soft contact lens (s cl), Intacs™ (Int), high myopia spectacles (sp hi), rigid contact lens (r cl), Artisan™ (Art), and LASIK.

Estimation of the Depth of Focus

Tables 6 to *10* show the experimental and theoretical depth of focus data at different pupil diameters. Experimental data are shown on the basis of averaged and individual contrast sensitivity data. Individual depth of focus could not always be measured: The optimum focus was so positive in some cases that the focus at which contrast sensitivity reached half its maximum value could not be determined. In other cases, there were double optimum foci. There was, however, never more than 1 dropout in each statistical analysis. Nevertheless, disregarding these cases could cause a small bias in which the individual depth of focus would be artificially low compared to the depth of focus based on the averaged contrast sensitivity. There was no significant difference in the depth of focus between the low myopia groups with 4.0 mm and 6.0 mm pupils ($P = .916$ and $P = .194$, respectively). The Intacs™ group had a significantly larger depth of focus with a 7.0 mm pupil than the soft contact lens group (P = .035). There was no statistically significant difference in depth of focus between the high myopia groups ($P > .05$).

Table 6. Experimental depth of focus in low myopic groups on the basis of average contrast sensitivity as a function of defocus. The depth of focus determined for a spatial frequency of 8 cpd was defined as twice the positive half of the dioptric range in which the contrast sensitivity exceeded half its maximum value.

	Depth of Focus (D) with Averaged Contrast Sensitivity		
Pupil Diameter (mm)	Spectacles	Soft Contact Lens	Intacs
4	1.53	2.18	1.57
6	1.41	1.45	1.90
7	1.28	1.45	1.77

Table 7. Experimental depth of focus in low myopia groups on the basis of individual contrast sensitivity as a function of defocus.

	Depth of Focus (D) (Mean ± SE) with Individual Contrast Sensitivity		
Pupil Diameter (mm)	Spectacles	Soft Contact Lens	Intacs
4	1.39 ± 0.13 (n = 10)	1.44 ± 0.21 (n = 7)	1.49 ± 0.18 (n = 10)
6	1.28 ± 0.15 (n = 10)	1.34 ± 0.08 (n = 7)	1.68 ± 0.22 (n = 9)
7	1.29 ± 0.08 (n = 10)	1.07 ± 0.05 (n = 8)	1.49 ± 0.15 (n = 10)

Table 8. Experimental depth of focus in high myopia groups on the basis of average contrast sensitivity as a function of defocus. The depth of focus determined for a spatial frequency of 8 cpd was defined as twice the positive half of the dioptric range in which the contrast sensitivity exceeded half its maximum value.

	Depth of Focus (D) with Averaged Contrast Sensitivity			
Pupil diameter (mm)	Spectacles	Rigid Contact Lens	Artisan Lens	LASIK
4	1.81	1.74	1.50	2.02
6	1.68	1.51	1.56	1.74
7	1.63	1.38	1.32	1.81

LASIK = Laser in situ keratomileusis

Table 9. Experimental depth of focus of high myopia groups on the basis of individual contrast sensitivity as a function of defocus.

	Depth of Focus (D) (mean ± SE) with Individual Contrast Sensitivity			
Pupil Diameter (mm)	Spectacles	Rigid Contact Lens	Artisan Lens	LASIK
4	1.50 ± 0.13 (n = 10)	1.99 ± 0.25 (n = 7)	1.31 ± 0.07 (n = 10)	1.81 ± 0.25 (n = 10)
6	1.33 ± 0.13 (n = 9)	1.22 ± 0.18 (n = 7)	1.23 ± 0.09 (n = 10)	1.45 ± 0.14 (n = 9)
7	1.37 ± 0.13 (n = 10)	1.73 ± 0.25 (n = 7)	1.46 ± 0.21 (n = 10)	1.63 ± 0.21 (n = 9)

LASIK = Laser in situ keratomileusis

Table 10. Depth of focus for theoretical eye models 1 and 2 with a 6.0 mm pupil. Various amounts of irregular aberration (IA) were implemented in the theoretical eye models.

	Theoretical Depth of Focus (D)		
Eye Model	IA = 0.3 D	IA = 0.5 D	IA = 0.7 D
1	1.36	1.66	2.04
2	1.01	1.38	1.82

Discussion

This study investigated the effect of different types of myopia correction on visual acuity, stray light, predictability,[15] contrast sensitivity, myopic shift, and depth of focus. In daily life, people usually do not wear additional correction for the remaining refractive error after myopia corrections. The UCVA and uncorrected contrast sensitivity function are therefore of interest. In the low myopia groups, the UCVA after myopia correction was better in the spectacles group than in the soft contact lens and Intacs™ groups. The latter 2 groups did not differ significantly from each other. The predictability in the Intacs™ group, which agrees with that in other studies,[2,16] was comparable to that in the spectacles group and slightly better than that in the soft contact lens group, although the small number of patients per group must be considered.

Since none of the contact lens wearers had visual complaints, they apparently tolerated an amount of defocus that was larger than the predictability in the Intacs™ group. This laxity in contact lens wearers has been described.[17] In the high myopia groups, the UCVA after myopia correction was significantly better in the spectacles group, followed by the rigid contact lens, Artisan™ claw lens, and LASIK groups. The low UCVA in the LASIK group can be explained by the low predictability. A large amount of stray light was measured in both contact lens groups compared to that in the other groups.

Uncorrected contrast sensitivity was not significantly different between the high myopia groups. One remarkable finding in the low myopia groups was the low uncorrected contrast sensitivity, especially at spatial frequencies between 3 cpd and 8 cpd (*Figure 2A*), in the spectacles group compared to that in the other low myopia groups and the contrast sensitivity at defocus level zero. Spherical defocus is not a likely cause of the contrast sensitivity attenuation. The remaining spherical correction measured while the subject wore his/her spectacles and the predictability of the spectacles were not significantly different from these factors in the other groups. Furthermore, the UCVA in the spectacles group was better than that in the other low myopia groups. A possible cause of the contrast sensitivity attenuation may be the change in astigmatism induced by the cycloplegic drops. In the low myopia spectacles group, 3 subjects had a cylindrical axis that changed more than 10 degrees after cycloplegia. In 2 of the 3, the astigmatic power changed 0.75 D. So the uncorrected contrast sensitivity measurements were performed under insufficient astigmatic correction in the low myopia spectacles group. This is known to cause local notches in the contrast sensitivity function.[18] Another possible explanation is the relatively small amount of aberration in the spectacles group, which leaves these individuals more vulnerable to defocus at certain spatial frequencies.

From Contrast Sensitivity to Aberrations

In this study, spherical and irregular aberrations were estimated by psychophysical measurement of defocus-specific contrast sensitivity. Both spherical and irregular aberrations influence myopic shift and depth of focus. Spherical aberration causes a myopic shift and increases depth of focus. Irregular aberration also increases depth of focus but at the same time decreases the effect of spherical aberration on myopic shift. To estimate the overall spherical and irregular aberrations with the different types of myopia correction, myopic shift and depth of focus data with a 6.0 mm pupil were compared to values found in theoretical eye models that simulated different amounts of spherical and irregular aberration. Optical calculations of lenses and corneal spherical aberration data, based on topography pictures, were also used.

Spectacles

Both spectacles groups had similar myopic shift and depth of focus values. Collectively, the data best match eye model 2 of Jansonius and Kooyman[10] with an irregular aberration of 0.5 D. Moreover, both groups agreed well with a large group of subjects in an earlier study,[4] who were within ± 2.0 D of emmetropia and had no significant astigmatism. The spherical aberration in the cornea (mean ± 1 SE) did not differ significantly between the 2 spectacles groups in this study (1.37 ± 0.08 D and 1.44 ± 0.08 D in the low and high myopic groups, respectively) and the abovementioned large group of emmetropic subjects (1.47 ± 0.04 D).[4] These values also agree with those of Kiely and coauthors,[19] who measured corneal spherical aberration by means of photokeratoscopy. Calculation of a planoconcave -10.0 D spectacle lens (Appendix) gives a spherical aberration of -0.04 D, which is clinically negligible. When a spherical aberration of 0.9 D is assumed for the entire eye, which is the case in eye model 2, the spherical aberration in the cycloplegic lens will be approximately -0.5 D. This negative value of spherical aberration compensates for the positive corneal spherical aberration described earlier[20,21,22] and agrees in magnitude with an earlier study by Tomlinson and coauthors.[23]

Contact Lenses

Flexible soft contact lenses are known to adopt the aspherical shape of the cornea, and thereby reduce any spherical aberration they might have.[24] This is illustrated by our measurement of the spherical aberration in the cornea with a soft contact lens (1.37 ± 0.13, mean ± 1 SE), which was identical to that in the spectacles group. The mean keratometric values (K1 and K2) of soft contact lenses were significantly flatter than those in the spectacles group, accounting for the myopia correction. Since no changes were made to the crystalline lens, we assumed that its spherical aberration was also -0.5 D. This agrees with the myopic shift and depth of focus data in the soft contact lens group, which is more or less similar to eye model 2 with an irregular aberration of 0.5 D. So, soft contact lenses do not appear to induce significant spherical or irregular aberration.

The back surface of a rigid contact lens should be made to fit the cornea well. By manipulating the shape of the lens' front surface, the spherical aberration of this on-eye contact lens can be altered without changing its dioptric power.[24,25] Unfortunately, we do not know what kind of rigid contact lenses our subjects had. Eyes with rigid contact lenses showed a myopic shift that was not compatible with eye model 1 or 2. Depth of focus data were also ambiguous with regard to the choice of eye model. Nevertheless, spherical aberration of a rigid contact lens can be calculated under the assumption of a spherical front and back surface (Appendix). For example, spherical aberration of a -13.0 D rigid contact lens is -0.8 D for a 6.0 mm pupil. When a spherical aberration of -0.5 D is presumed for the cycloplegic lens, the overall spherical aberration of the eye with a rigid contact lens will be -1.3 D. This negative spherical aberration agrees with the location of the optimum focus of contrast sensitivity at 4 cpd, which lies to the hyperopic side of the optimum focus at 16 cpd.

Intacs™

The Intacs™ rings flatten the pericentral area of the cornea more than its center and thus preserve the prolate shape of the central optical zone. This minimizes spherical aberration in relation to myopia corrections which convert the prolate corneal shape into an oblate one.[26] As in the rigid contact lens group, myopic shift and depth of focus data with the Intacs™ rings do not allow comparison with either eye model. Again, the optimum focus at 4 cpd was located on the hyperopic side of the optimum focus at 16 cpd, which implies a negative spherical aberration. Depth of focus with a 4.0 mm pupil was comparable to that in the spectacles group, while the depth of focus with 6.0 mm and 7.0 mm pupils was much larger. This might be due to irregular aberration caused by the location of the ring segments: The inner and outer diameters were 6.8 mm and 8.1 mm, respectively. The 0.3 D corneal spherical aberration was significantly lower than that in the spectacles and soft contact lens groups. Presuming a spherical aberration of -0.5 D for the cycloplegic lens, the overall spherical aberration would be -0.2 D, which agrees with the positive myopic shift.

Artisan™ Claw Lens

Uneventful implantation of an Artisan™ claw lens does not affect the shape of the cornea. This is illustrated by our measurement of postoperative corneal spherical aberration (1.49 D), which was similar to that in the spectacles group. Assuming a 0.04 m radius for the front curvature, which we deduced from a construction drawing,[3] the spherical aberration of the IOL was calculated to be -0.6 D (Appendix). When a -0.5 D spherical aberration of the cycloplegic human lens is presumed, the spherical aberration of an eye with an Artisan™ claw lens will be 0.4 D (1.49 – 0.6 – 0.5). Additional irregular aberration and minor decentrations may account for the hyperopic, ie, positive myopic shift, and depth of focus data found.

Laser in Situ Keratomileusis

The patients in this study were operated on between October 1996 and February 1998. Since then, LASIK technology has improved and the dioptric indication to perform LASIK has been changed to myopia of less than -12.0 D. In the present study, 3 patients had a preoperative spherical equivalent correction larger than -12.0 D. So the population may not be representative today. However, LASIK remains the only correction method in this study that irreversibly changed the shape of the central cornea. This change did not result in a significant increase in stray light but did significantly increase corneal spherical aberration to almost 6.0 D (*Figure 7*). Accordingly, myopic shift was largest in this group.

Using a laser ray-tracing technique, Moreno-Barriuso *et al.*[27] objectively measured a factor 4 increase in spherical aberration after LASIK, which agrees with our data. Wavefront-guided LASIK, as shown by Mrochen and coauthors,[28] also demonstrated an increase in spherical aberration. The change from a prolate corneal form to an oblate one is the probable cause of the increase in spherical aberration. The myopic shift in our LASIK group, however, did not differ much from that in the spectacles group. This may be explained by the presence of an increase in irregular and other aberrations that attenuate the effect of spherical aberration on myopic shift. For example, the Moreno-

Barriuso group found that coma aberrations also increased significantly. They measured a factor 1.9 increase in the root-mean-square wavefront error, which was used as a measure of global image quality. They also noted that the modulation transfer function was significantly higher preoperatively than after LASIK.

The presence of other aberrations would explain why the LASIK group in our study had a larger depth of focus than the spectacles group. Another attenuating effect on spherical aberration based on measurements of the anterior cornea could be bulging of the posterior cornea after LASIK treatment as noted by Marcos and coauthors.[29] Based on the myopic shift, we could rank the spherical aberration of LASIK between that of the reduced and schematic eye models. Given a spherical aberration of -0.5 D for the cycloplegic lens, the overall spherical aberration is 5.2 D, which agrees with the amount present in the reduced eye.[10]

Comparison of Myopia Corrections

The possible advantage of aberrations is a relatively large depth of focus without a significant loss of contrast sensitivity or visual acuity.[4] Our study showed no significant interaction between pupil diameter and defocus level in low or high myopes. That is, 6.0 mm or 7.0 mm pupils did not show a lower depth of focus than the 4.0 mm pupil. This can be explained by the effect of aberrations that increase depth of focus at large pupil diameters, compensating the attenuating effect of larger pupil diameters on depth of focus.

The Intacs™ group showed similar visual acuity, stray light, and contrast sensitivity values but a higher depth of focus when compared to more conservative methods of myopia correction. Nevertheless, the risks and inconveniences of operating on an otherwise healthy eye remain. Another alternative for low myopes is PRK. This technique is, however, associated with a possible increase in glare, diminished mesopic vision, and reduced contrast sensitivity.[30,31,32,33]

We studied 2 alternative surgical methods for highly myopic individuals: Artisan™ claw lens and LASIK. In contrast to the Artisan™ claw lens, LASIK showed low UCVA and diminished contrast sensitivity at defocus level zero compared with the spectacles group. A recent study by El Danasoury and coauthors[34] showed similar results: most of their patients, who had Artisan™ claw lens implantation in 1 eye and LASIK in the other eye, preferred the IOL because of better vision quality. The larger depth of focus measured in the LASIK group in this study probably does not compensate for the decrease in visual acuity and contrast sensitivity. Nevertheless, older presbyopic individuals may benefit from it.

New algorithms are being designed for LASIK to customize higher-order aberrations. Bille[35] even postulates a preoperative simulation of visual outcome with the use of adaptive optics. This would make individual fine tuning of optical aberrations possible. Algorithm designers for excimer laser therapy and IOL architects are working to alter optical aberrations. Problems to conquer are technical (ie, problems with centration, accuracy, and varying reactions of biological tissue) and optical (eg, changing aberrations with accommodation and age).

Conclusions

There are several options available for myopes today, each with its own profile in visual acuity, stray light, and contrast sensitivity. Another important parameter of vision quality besides visual acuity, stray light, and contrast sensitivity is depth of focus. The trade-off between visual acuity and depth of focus is controlled by optical aberrations. It is likely that quality of vision will depend on the optimization of these aberrations and not minimization. Neither the surgical techniques nor the contact lenses studied resulted in a BCVA or contrast sensitivity that surpassed the values measured in the best corrected spectacles groups.

Appendix

Spherical Aberrations in a Spectacle Lens, a Rigid Contact Lens, and in the Artisan™ Claw Intraocular Lens

Calculation of the Spherical Aberration in a -10.0 D Planoconcave Spectacle Lens

The spherical aberration in a planoconcave spectacle lens can be calculated using the following equation:[36]

$$P_{sa}(h) = \frac{n^2 \ x \ h^2 \ x \ P}{2n'^2 \ x \ R^2} \qquad (2)$$

where P_{sa} is the power of the spherical aberration, n the refractive index in object space (1.5 for glass), n' the refractive index in image space (1.0 for air), h the distance from the center of the cornea (ray height), R the radius of the surface, and P the power of the surface (-10.0 D). R can be calculated from P, using the following equation:

$$R = \frac{n' - n}{P} \qquad (3)$$

which results in a radius of 50.0 mm. For a 6.0 mm pupil (h is 0.003 m), the spherical aberration of a -10.0 D spectacle lens equals -0.04 D.

Calculation of the Spherical Aberration in a -13.0 D Rigid Contact Lens

To calculate the spherical aberration in a -13.0 D rigid contact lens, a spherical front and back surface of the lens was assumed. In case of a good fit, the radius of the back surface of the contact lens is equal to the radius of the cornea. If the radius of the cornea is 7.7 mm, the power of the cornea without a rigid contact lens is 43.0 D, with n' = 4/3 for water and n = 1.0 for air. The power of the back surface of the rigid contact lens equals -20.0 D, with n = 1.49 for poly(methyl methacrylate). To have an overall power of -13.0 D, the power of the front surface would have to be 43-13+20 = 50 D. Using equation 2, the spherical aberration of the front surface equals 0.12 h^2, while that of the back surface equals -0.21 h^2. For a 6.0 mm pupil, the spherical aberration of a -13.0 D rigid contact lens equals -0.84 D.

Calculation of the Spherical Aberration in a -10.0 D Artisan™ Claw Lens

From a construction drawing, it was deduced that the front surface of the Artisan™ claw lens[3] is slightly curved with a front surface radius of 0.04 m. The back surface radius is 0.01 m for a -10.0 D lens. The lens is placed in the anterior chamber, which has an approximate refractive index of 4/3. The refractive index of this PMMA lens is approximately 1.49. Using equation 3, the powers of the front and back surfaces of the lens were calculated to be 4.0 D and -14.0 D, respectively. The spherical aberrations of the front and back surfaces of the lens were calculated for a 6.0 mm pupil using equation 2 and found to be 0.01 D and -0.63 D, respectively. Thus, the overall spherical aberration of a -10.0 D Artisan™ claw lens is -0.62 D.

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